

# How strange is high- $p_T$ physics at RHIC?

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Julia Velkovska



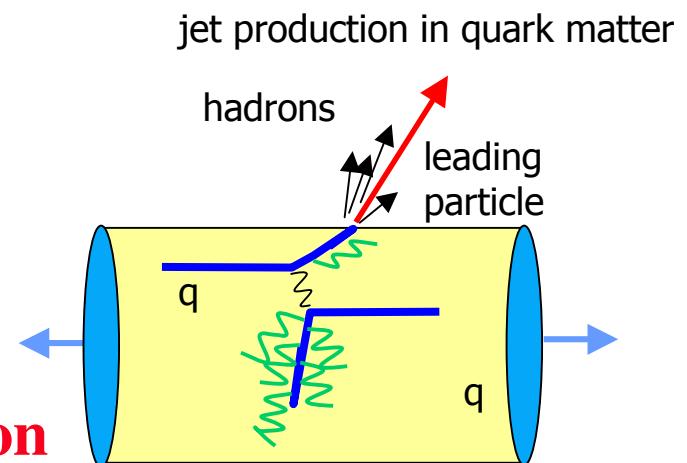
# Keyword definitions

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- In this talk “high- $p_T$ ” means  $p_T > 2\text{GeV}/c$
- “strange”
  - Anything that is has controversial explanations
  - Anything containing a strange quark and the measurement extends to  $p_T > 2 \text{ GeV}/c$
- Luckily, after 2 RHIC runs ... too many results to cover
  - Give priority to newer results
  - And results that provoked the largest number of pre-print papers from theorists

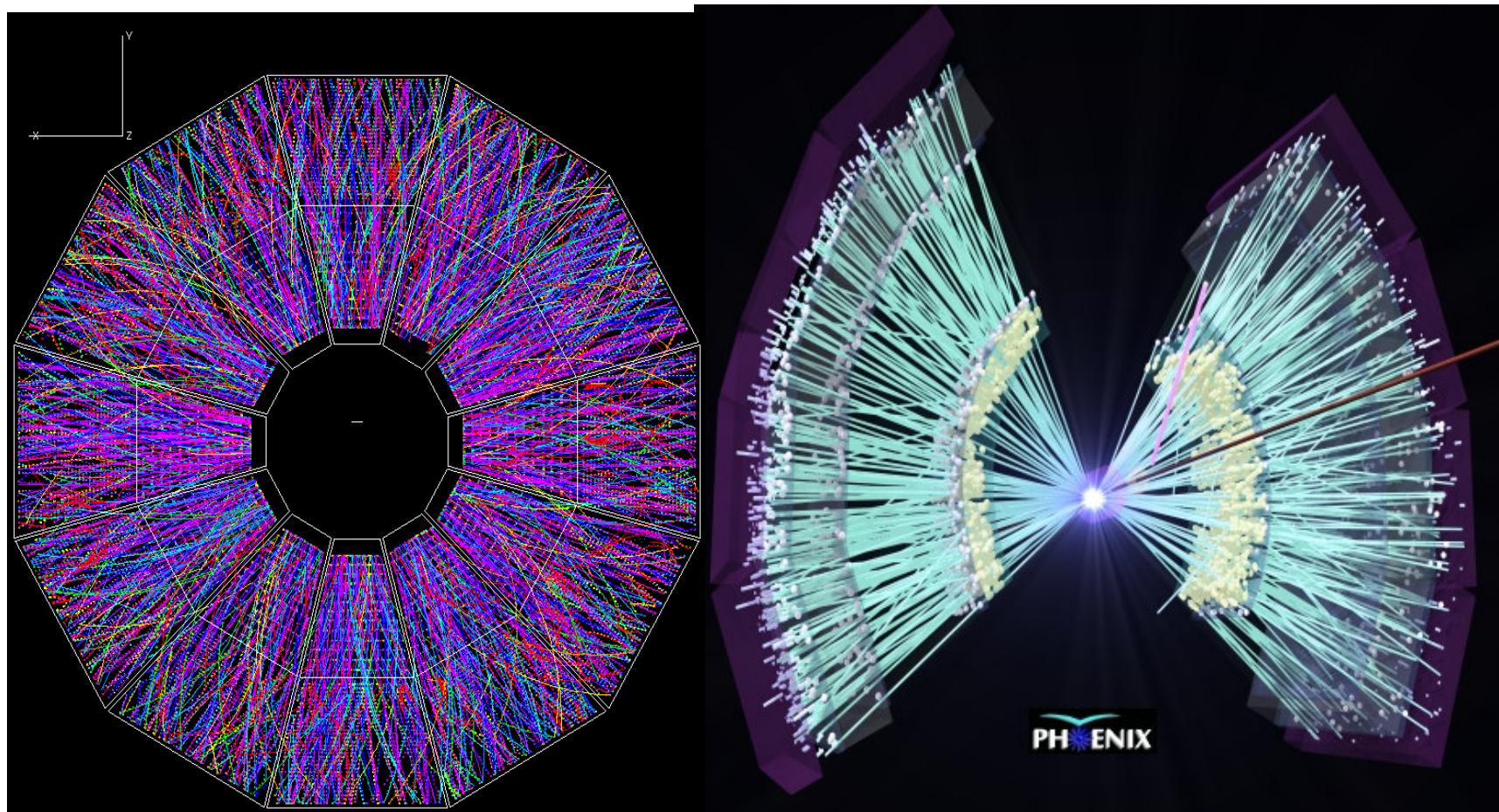
# Why study high- $p_T$ physics at RHIC ?

- New penetrating probe at RHIC
- in colored “quark matter”  
partons expected to lose  
significant energy via gluon  
bremsstrahlung
  - attenuation or absorption of jets  
“jet quenching”
  - suppression of high  $p_T$  hadrons
  - modification of angular correlation
  - changes of particle composition

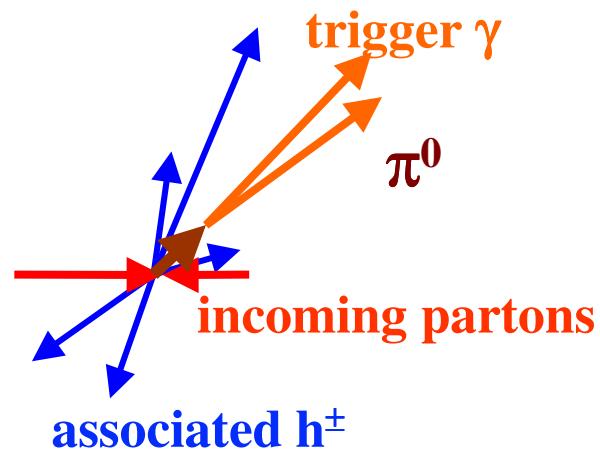


# Can we find jets in Heavy Ion Collisions ?

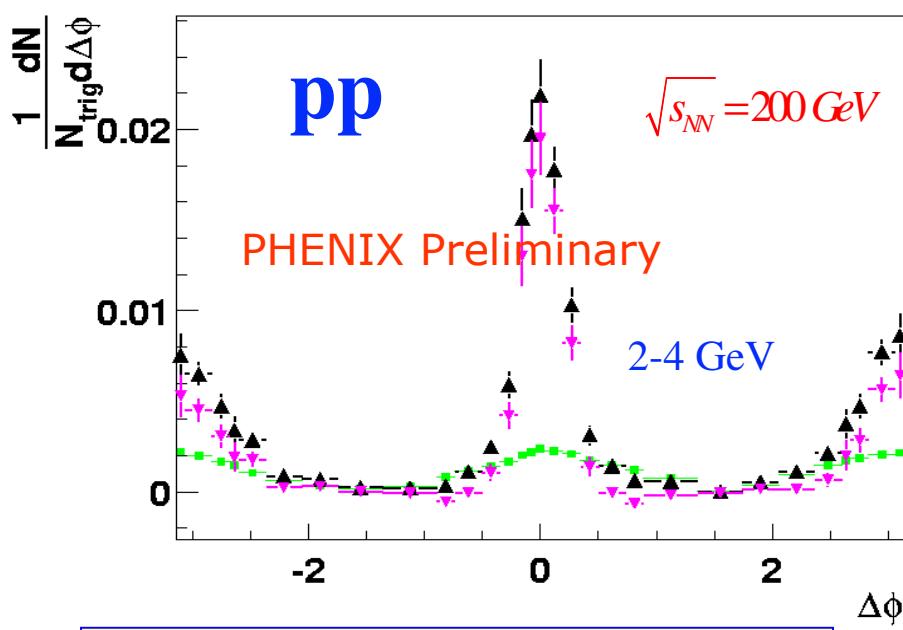
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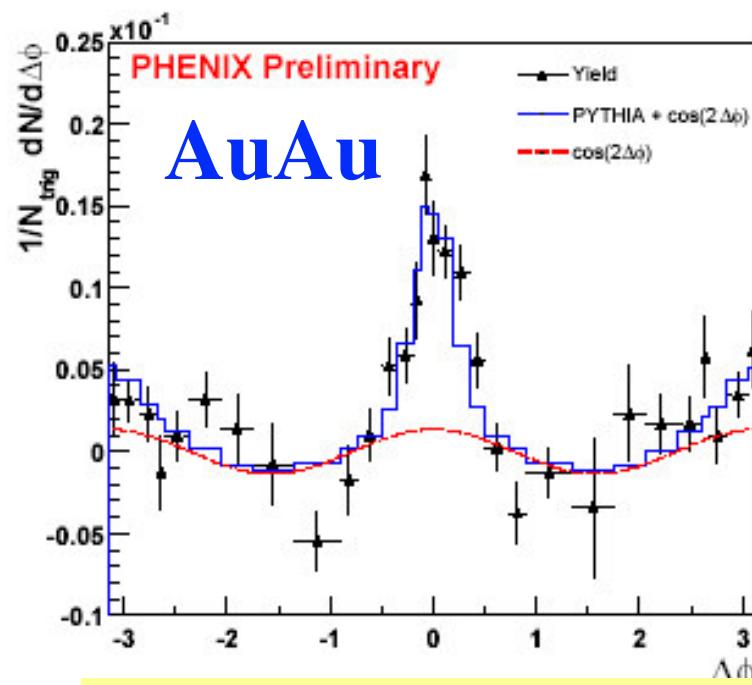
# The PHENIX approach: Leading Photon Correlations



- Select events with a photon of  $p_T > 2.5 \text{ GeV}/c$ . Mostly  $\gamma$ 's from decay of a high  $p_T \pi^0$  (leading particle)
- Build distributions in delta  $\phi$  -space of the charged hadrons relative to the trigger photons.



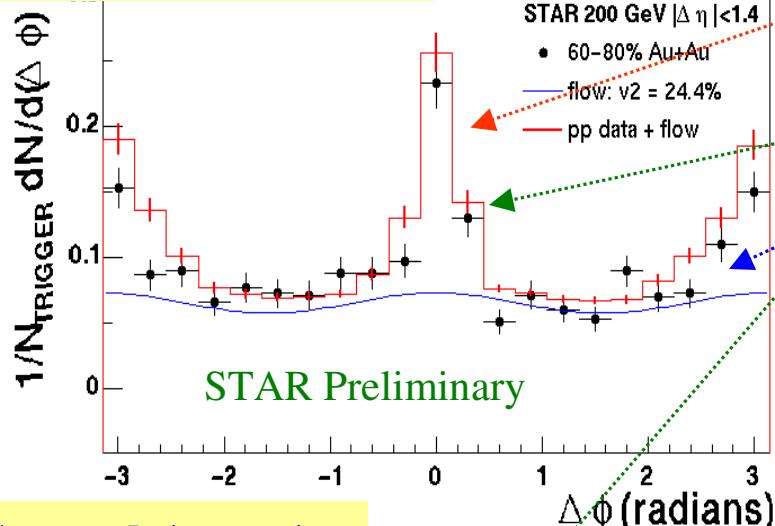
- black = pair distribution
- green = mixed event pair distribution
- purple = bkg subtracted distribution



In AuAu: add v2 component

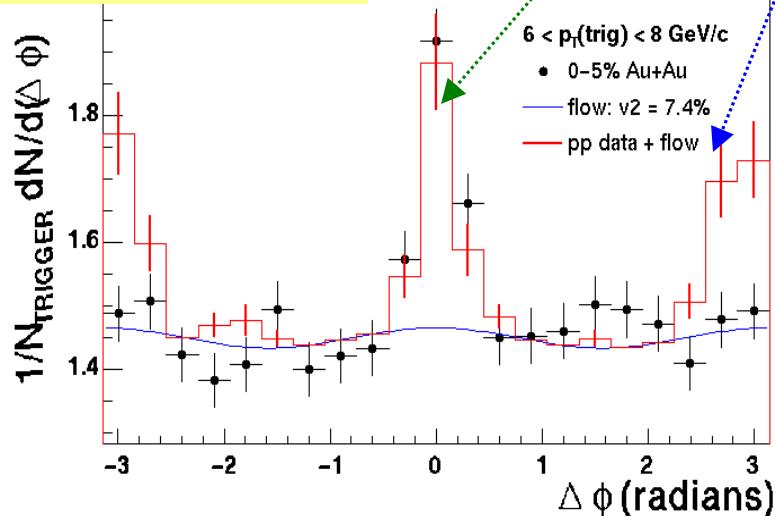
# Jets via charged-charged correlations:STAR

## Peripheral Au + Au

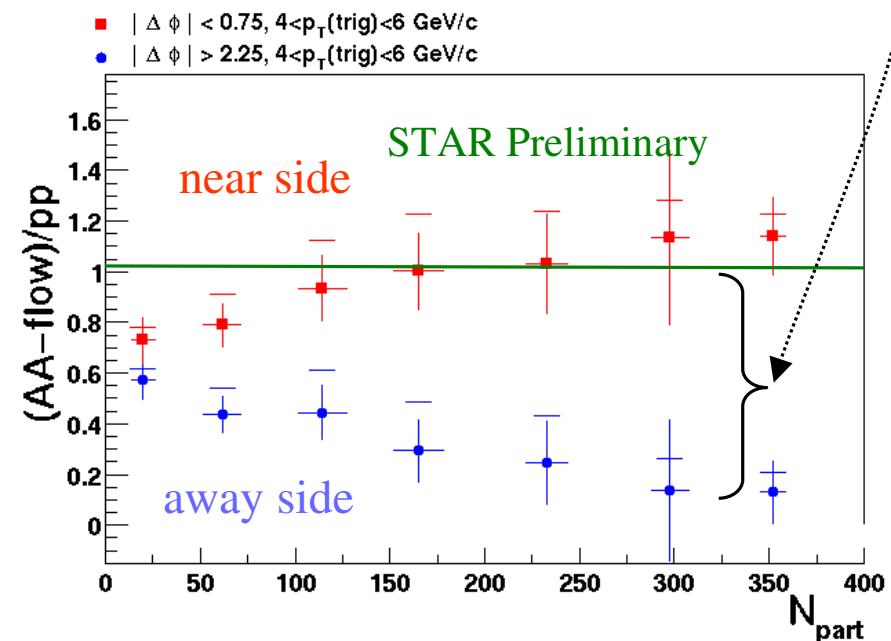


$$C_2(Au+Au) = C_2(p+p) + A \cdot (1 + 2v_2^2 \cos(2\Delta\phi))$$

## Central Au + Au

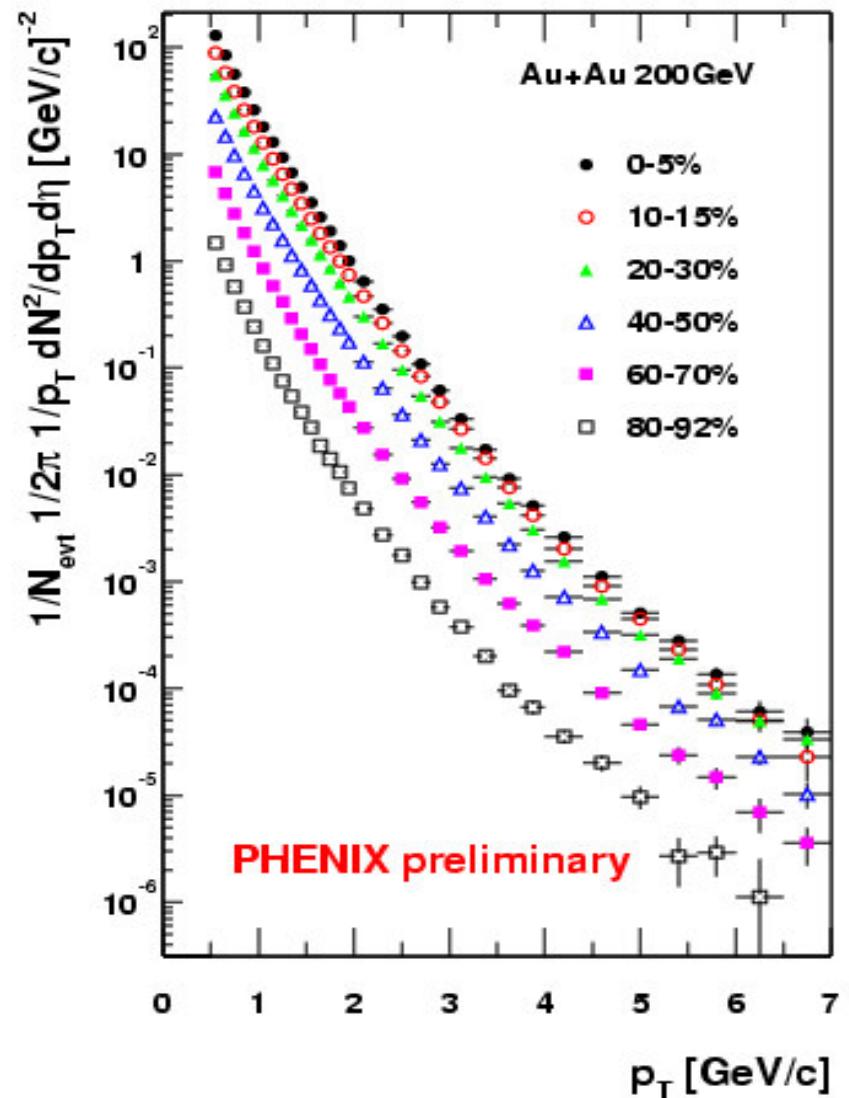
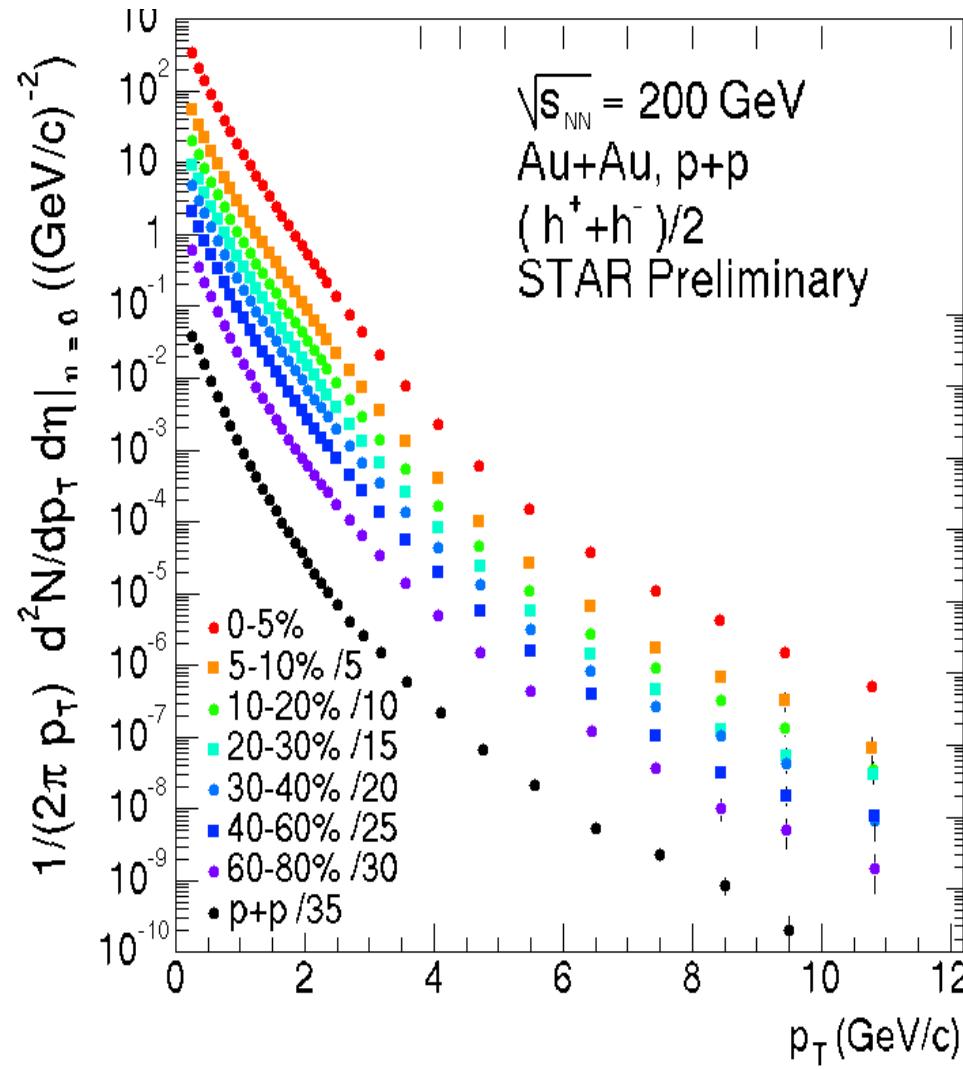


- Near-side well-described
- Away-side suppression in *central* collisions

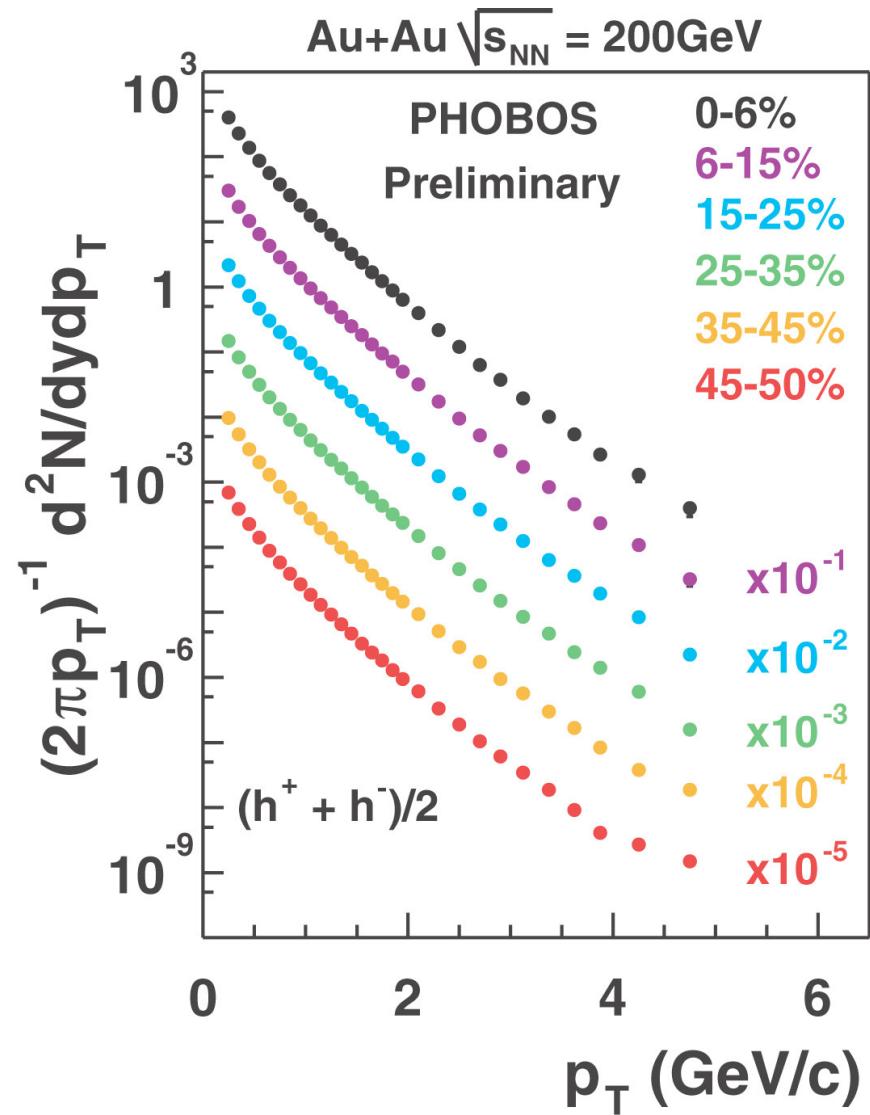
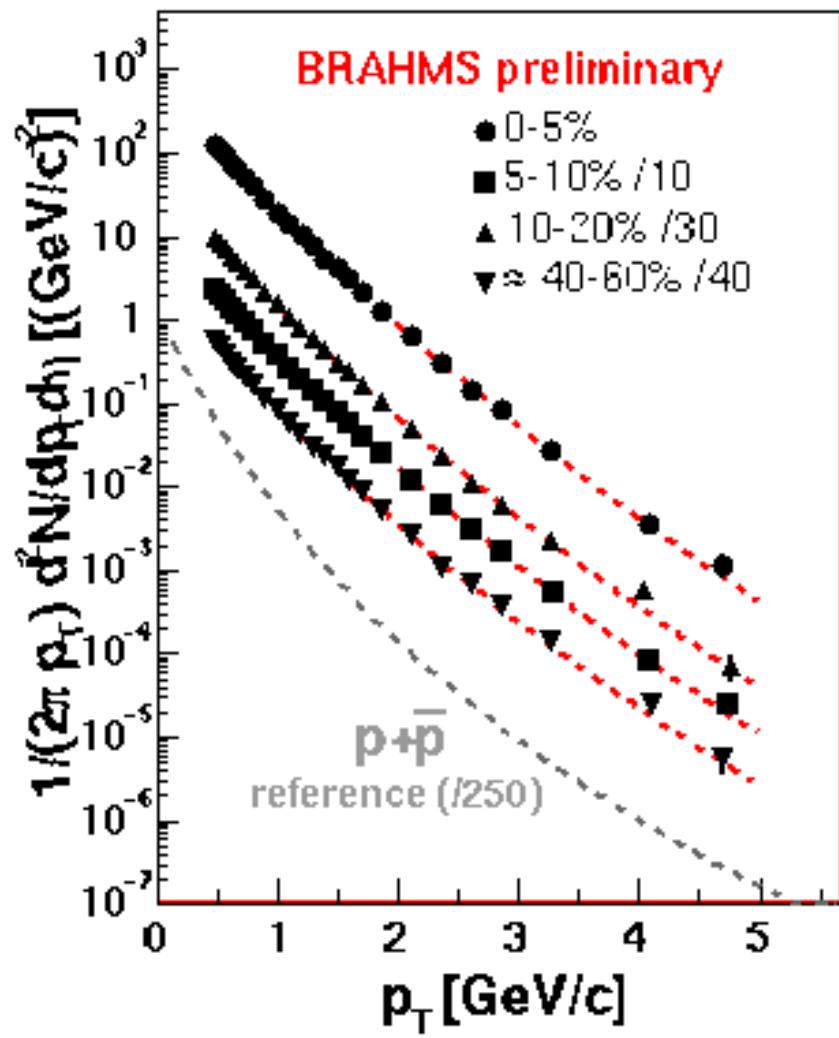


Away side jets are suppressed!

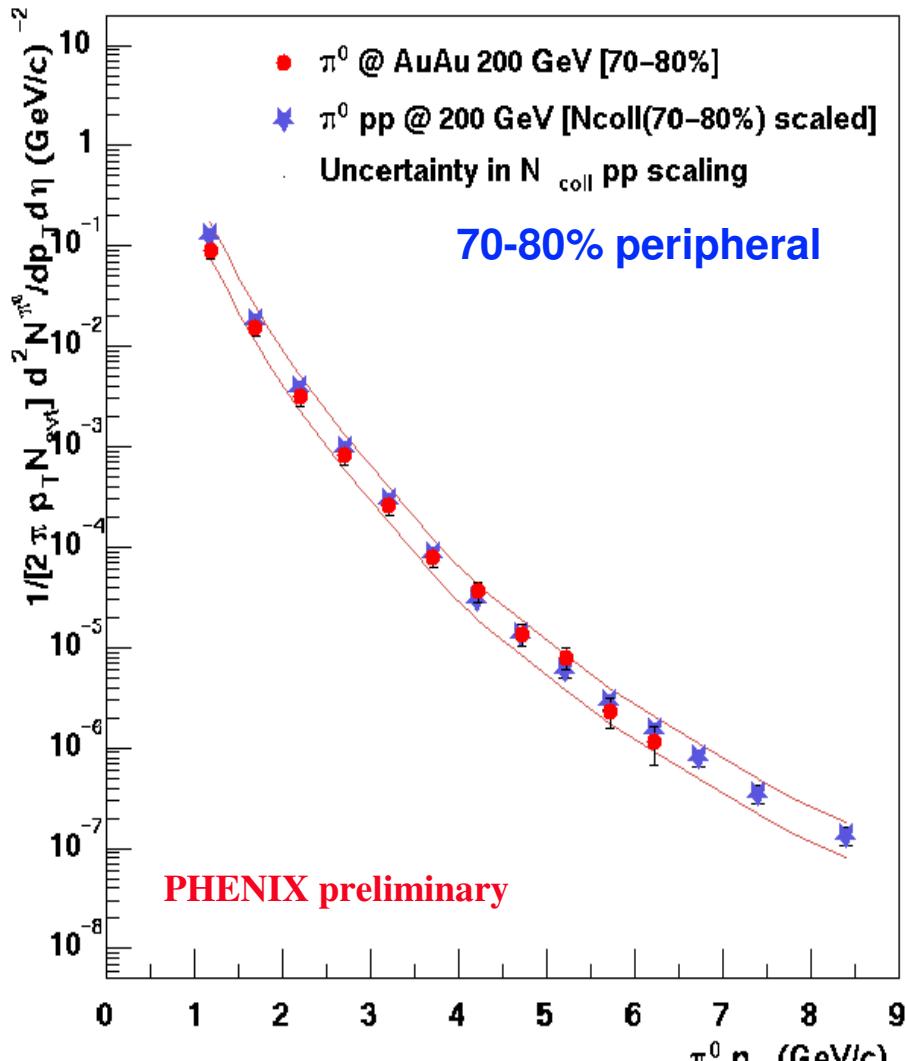
# High- $p_T$ Hadron Data from all RHIC Experiments



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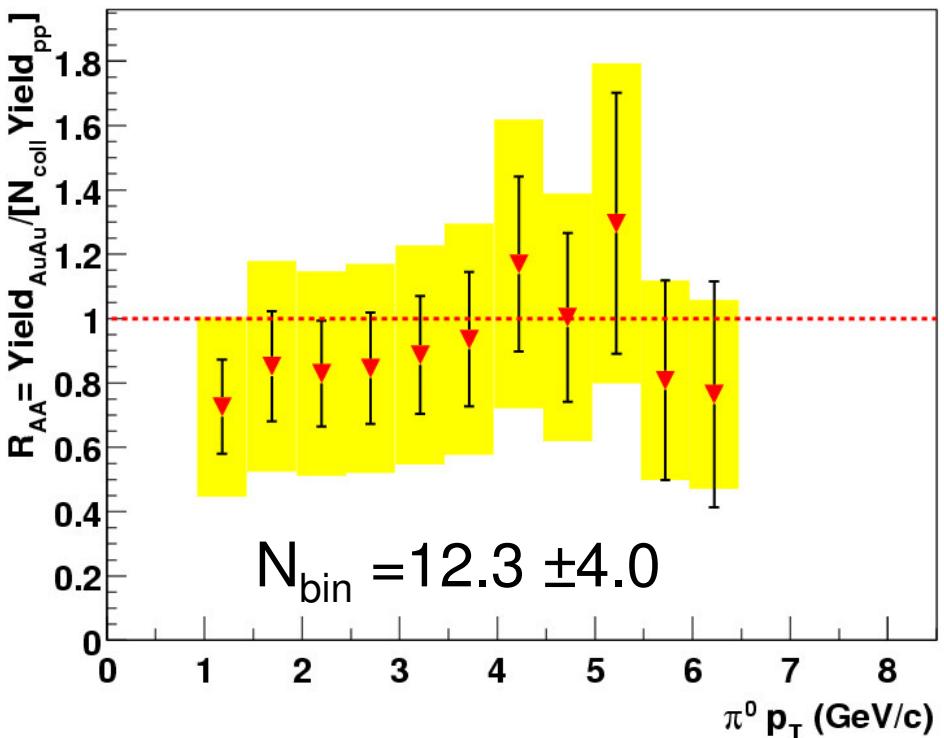


# Identified $\pi^0$ from PHENIX: pp, AuAu



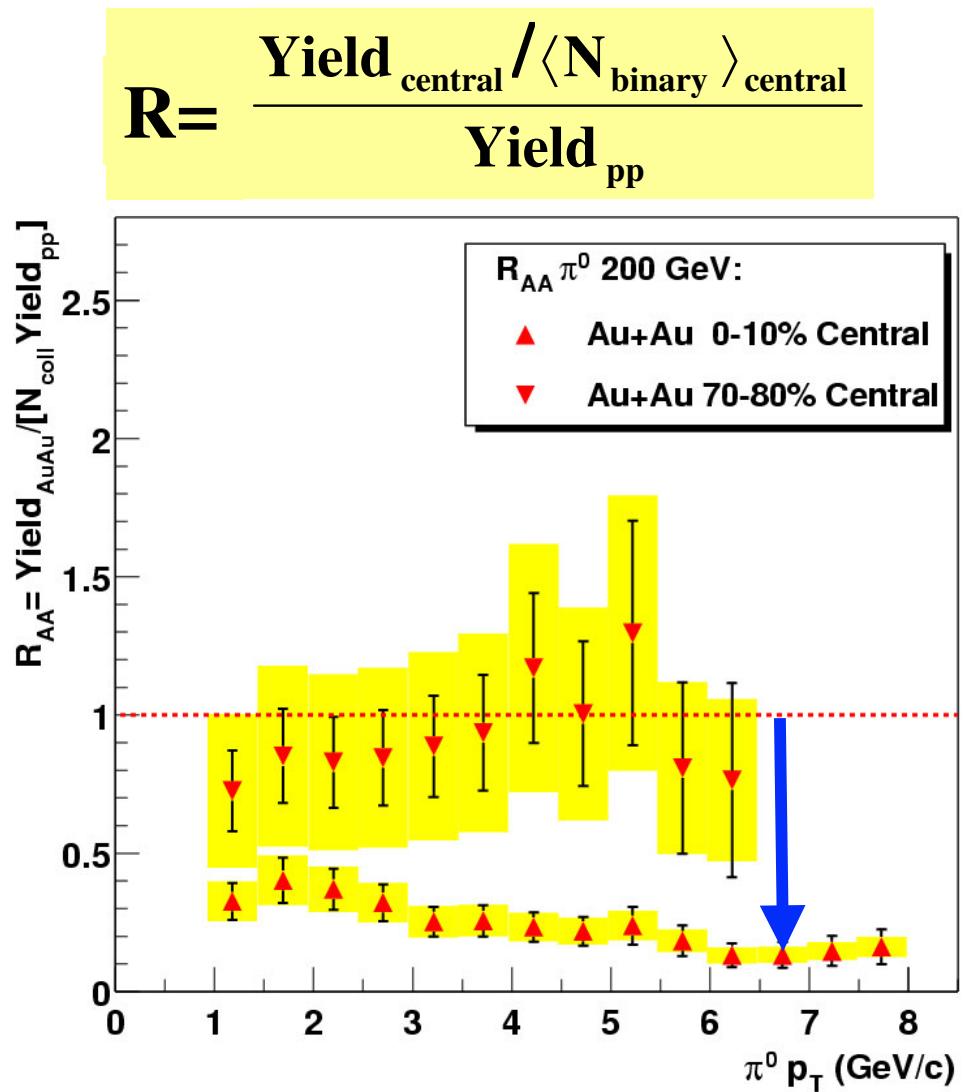
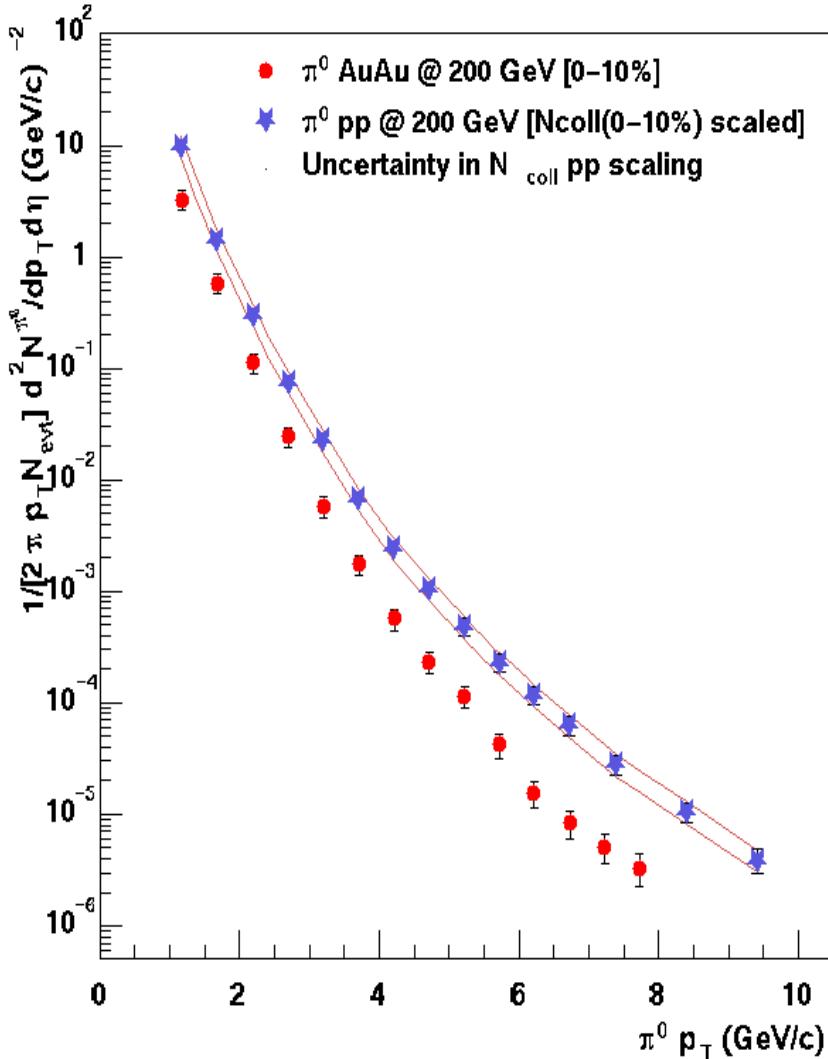
pQCD calculation LEVAI et. al., Y. Zhang,  
PRC65 (2002) 034903

$$R_{AA} = (\text{Yield}_{AA}/N_{\text{bin}})/\text{Yield}_{pp}$$



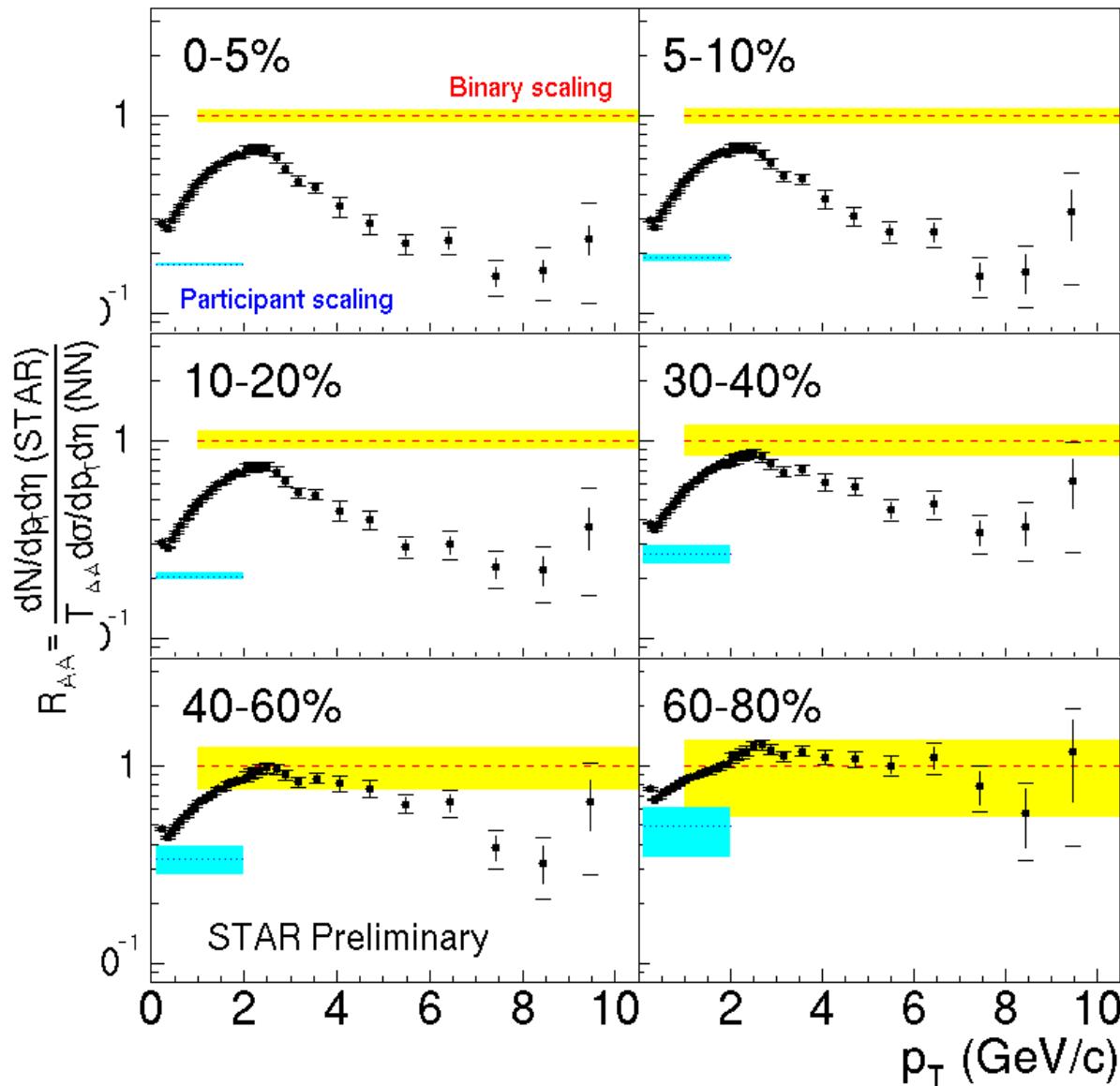
Peripheral AuAu  
consistent with hard-scattering

# Suppression of $\pi^0$ in Central AuAu Collisions



High  $p_T$  suppressed by factor  $\sim 5$   
pp to central AuAu and peripheral to central Au-Au

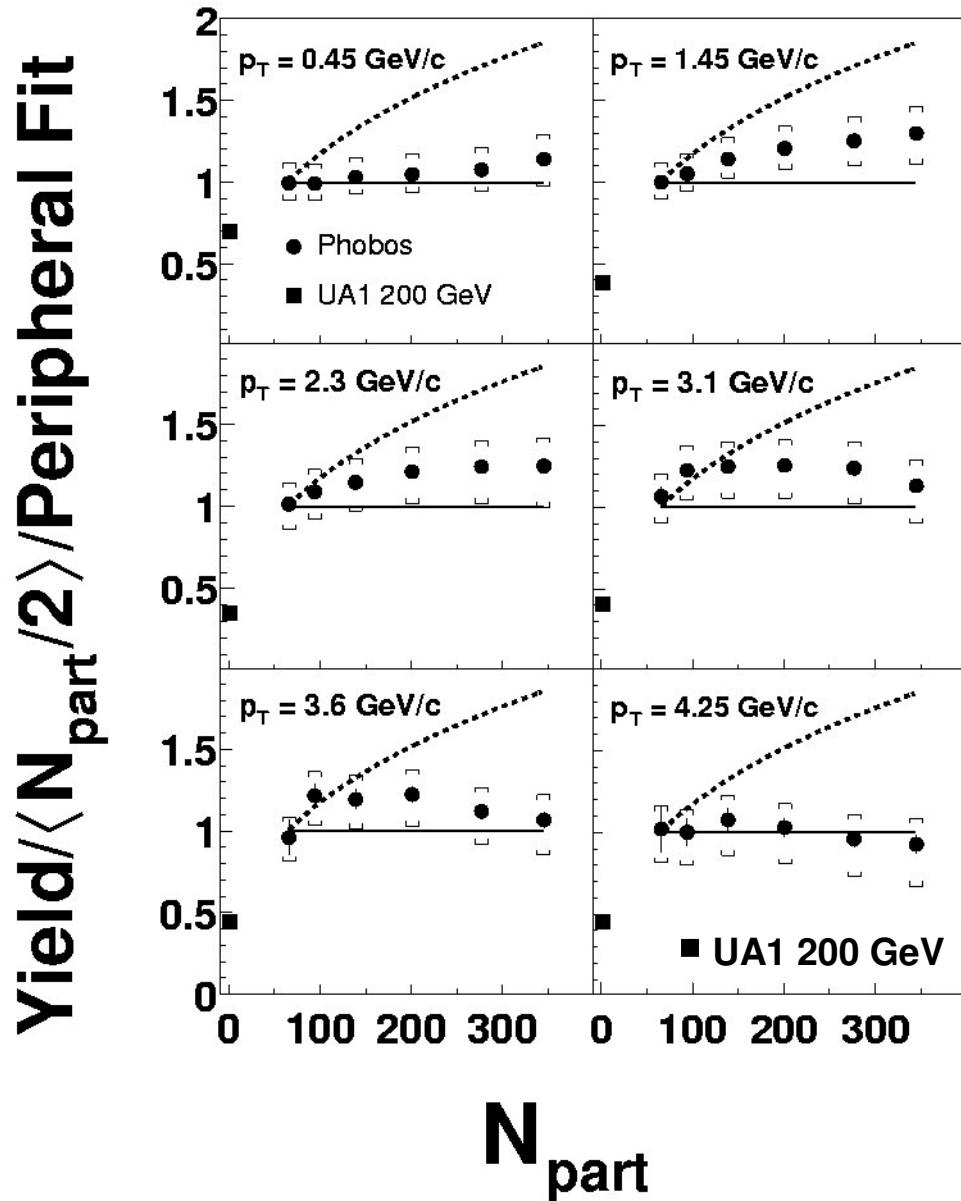
# $R_{AA}$ for charged hadrons



suppression  
increases up to  
 $p_T = 6 \text{ GeV}/c$

suppression  
saturates beyond  
 $p_T \sim 6 \text{ GeV}/c$

# Results from PHOBOS: Centrality scaling in $p_T$ bins



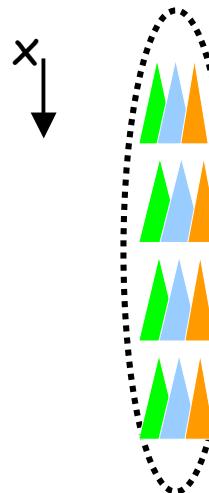
Spectra normalized to a fit to the  $p_T$  spectrum at  $N_{\text{part}} = 65$   
( 45-50% )

Low and high  $p_T$ :  
scaling with  $N_{\text{part}}$

Submitted to Phys.Lett.

# Gluon Saturation at Small $x_T$

**initial state effect**



D. Kharzeev, E. Levin Nucl-th/0108006

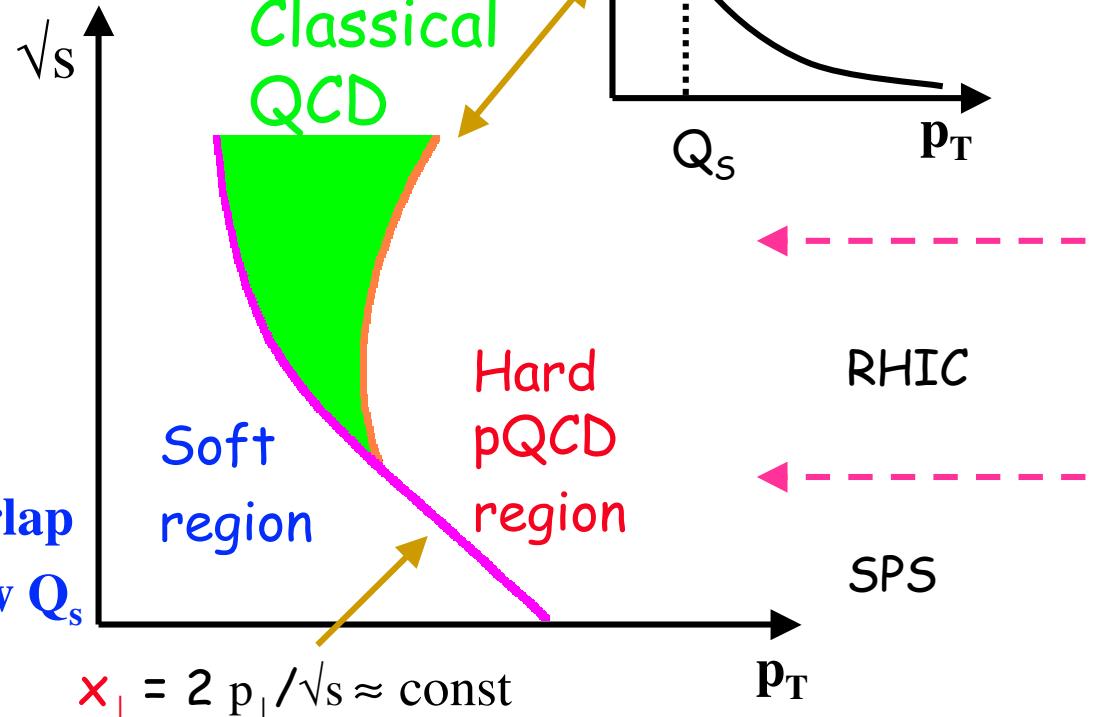
$$xG(x, Q^2)$$

**at small Bjorken  $x$ :**

- partonic wave functions overlap
- gluon density saturates below  $Q_s$

**saturation scale  $Q_s$**

- increases with  $\sqrt{s}$
- increases with centrality

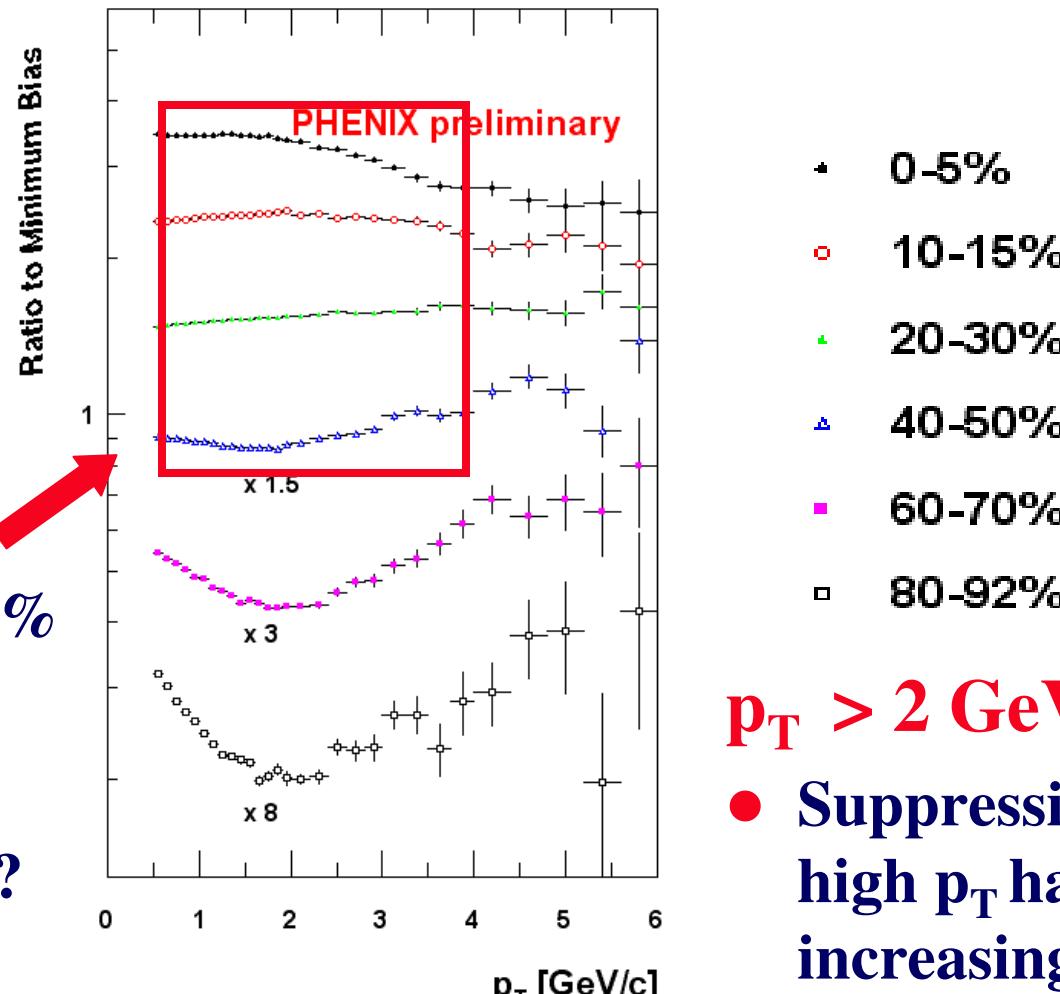


Reduced particle production compared to binary scaling.  
Away side jet not produced.

# Spectral shape evolution with centrality

$p_T < 2 \text{ GeV}/c$

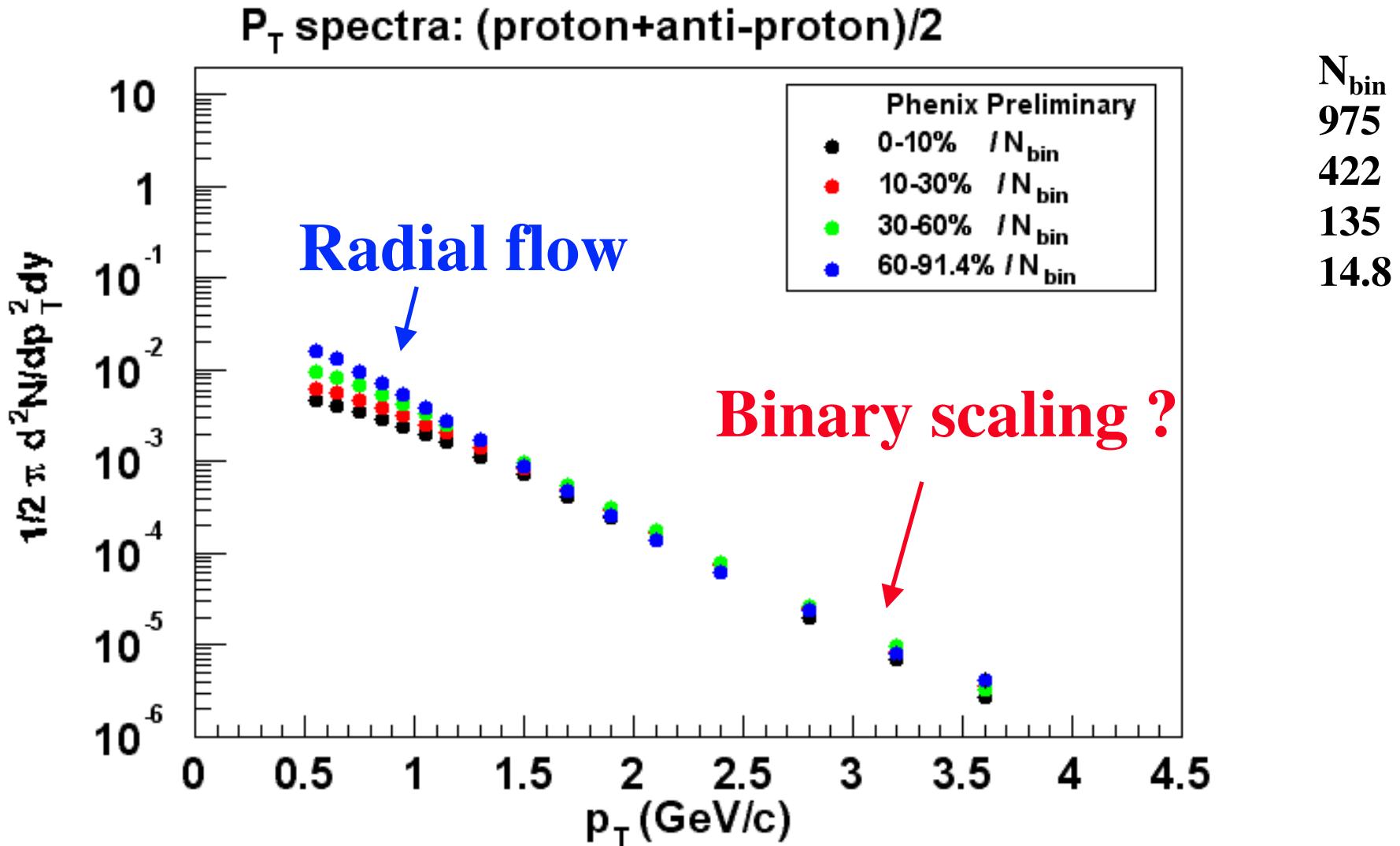
- Inverse slope increases with centrality due to radial flow
- Relatively little change from 0 – 50 % and  $p_T < 4 \text{ GeV}/c$
- But does this confirm saturation ?
- dAu data will give the answer



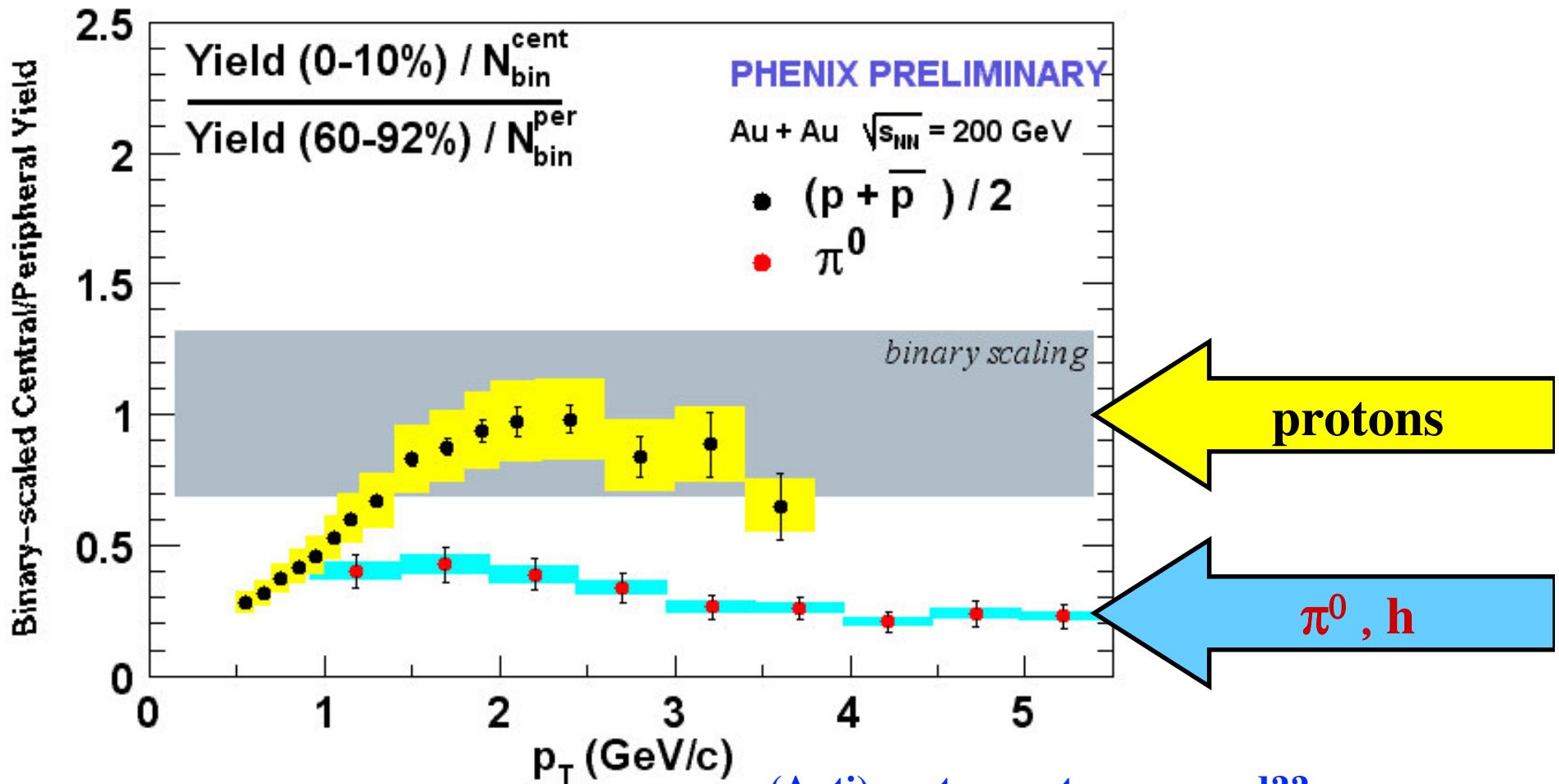
$p_T > 2 \text{ GeV}/c$

- Suppression of high  $p_T$  hadrons increasing with centrality

# Species dependent scaling behavior



# Are protons and anti-protons suppressed ?

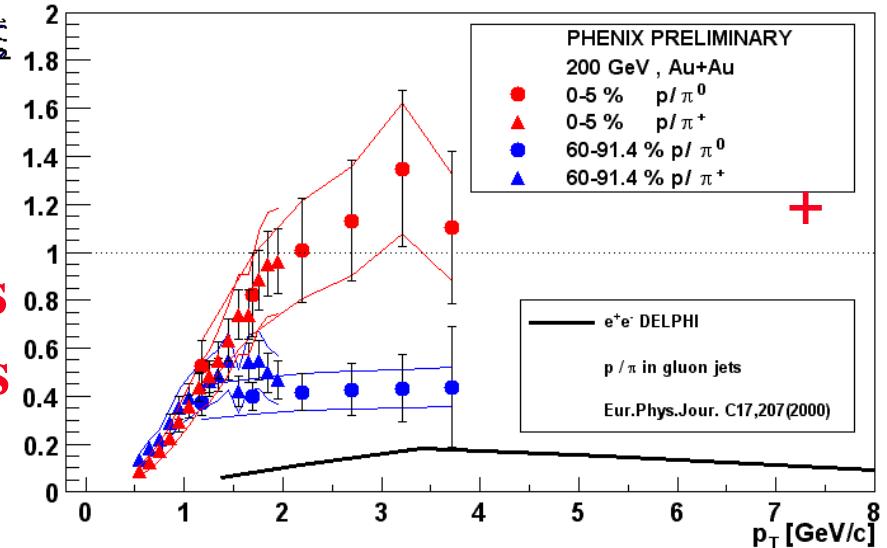


(Anti) protons not suppressed??  
Initial state effect ala Cronin?  
Medium modified fragmentation functions?  
What happens at higher  $p_T$ ?

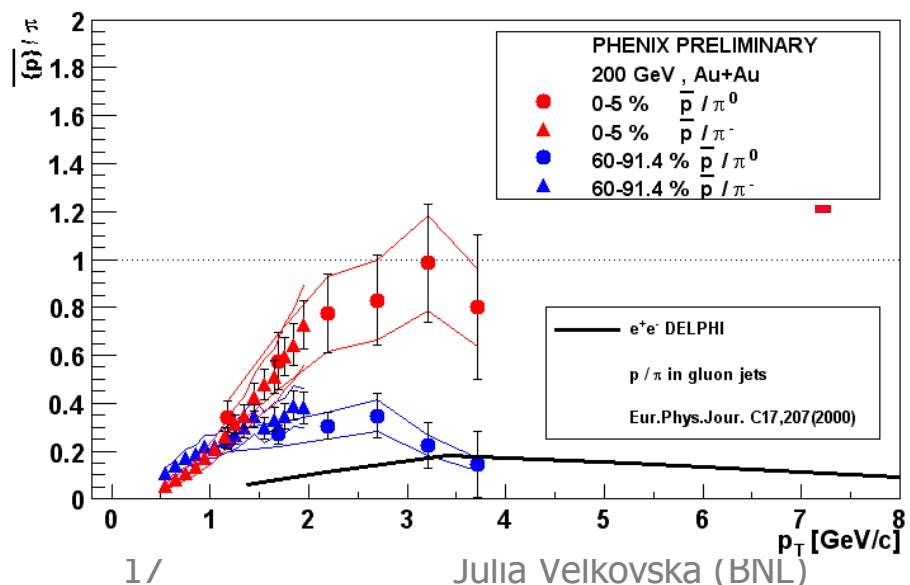
# But ... don't quite fit into a “hard” description

- $p/\pi$  for Au-Au collisions at  $p_T > 2 \text{ GeV}/c$

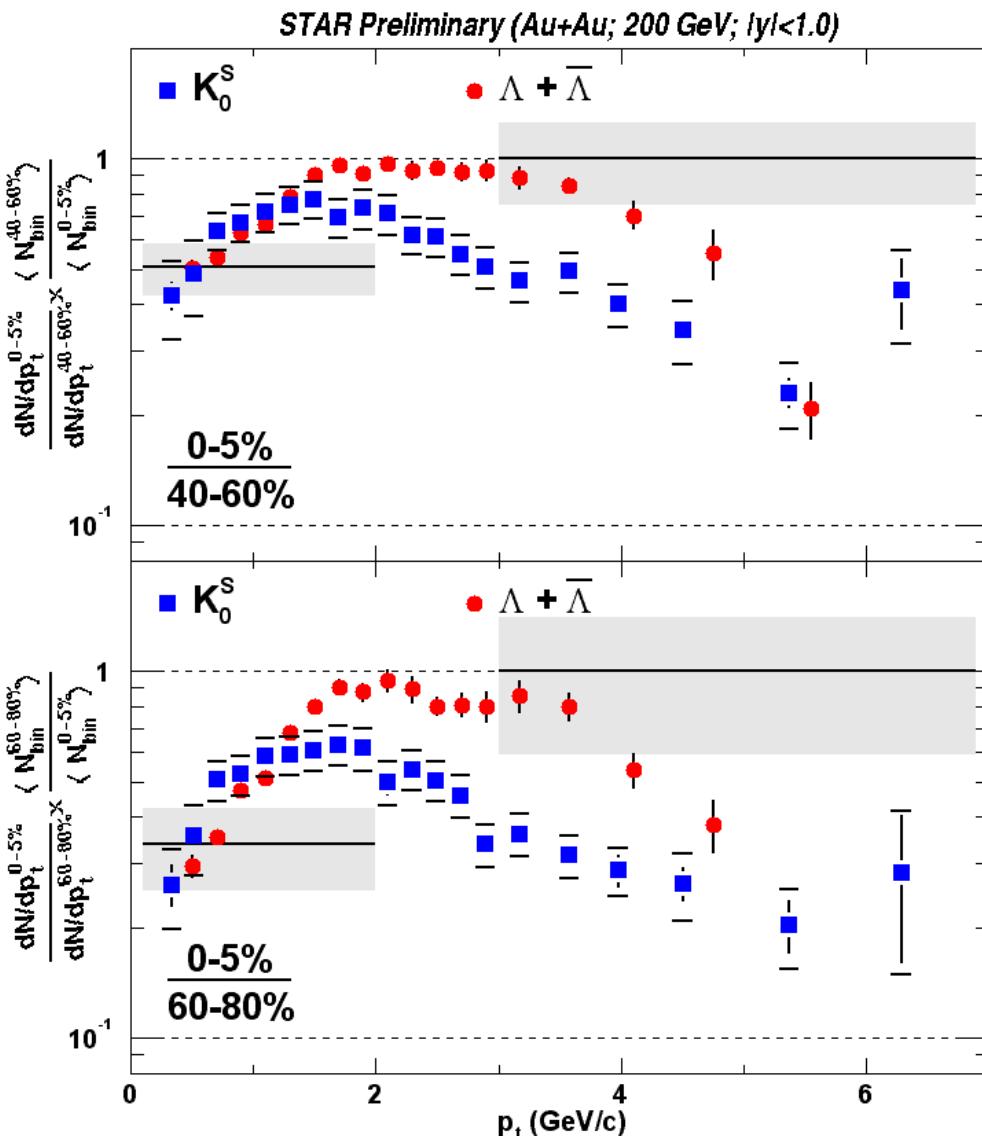
- ~1 for central collisions
- ~0.4 for peripheral collisions
- ~20% lower for anti-protons
- above ISR value  $\bar{p}/\pi \sim 0.17$
- above gluon jet value



The observed (anti)protons  
do not come from  
standard fragmentation!!



# Baryons vs mesons for strange particles

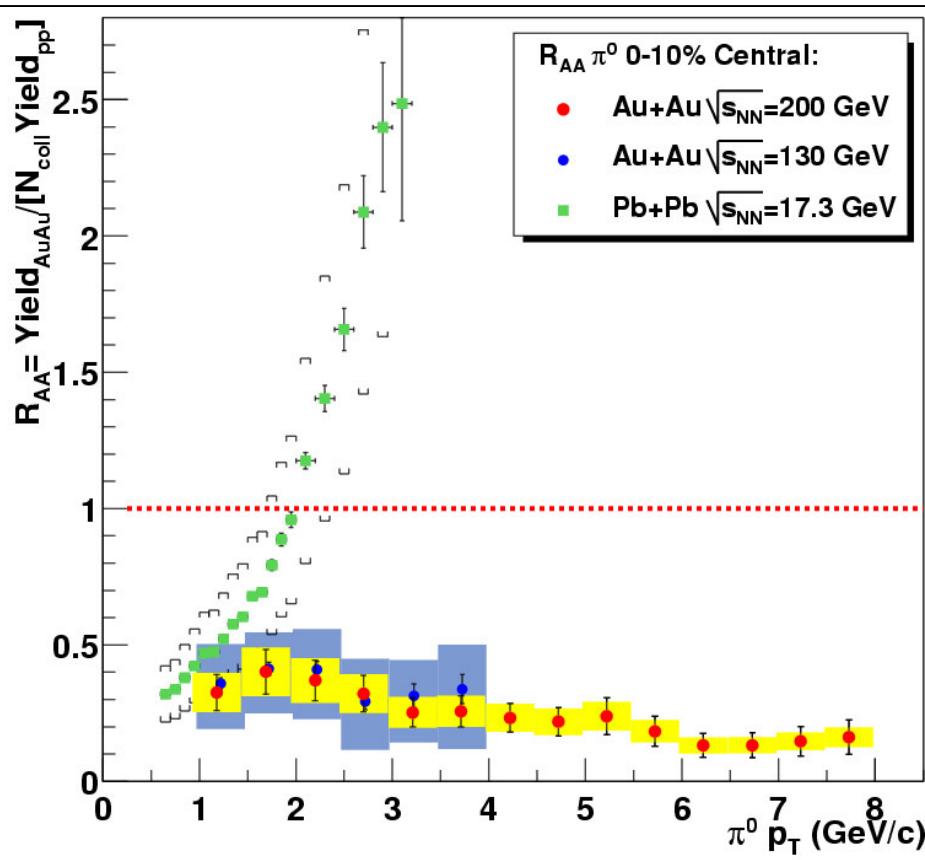


- $\Lambda$  vs  $K_s$  show the same behavior as  $p$  vs  $\pi$  up to  $\sim 4$  GeV/c
- Suppression of  $\Lambda$  sets in at higher  $p_T$
- Significant difference observed over  $\sim 3$  units of  $p_T$
- Is this a mass effect or a baryon/meson effect ?

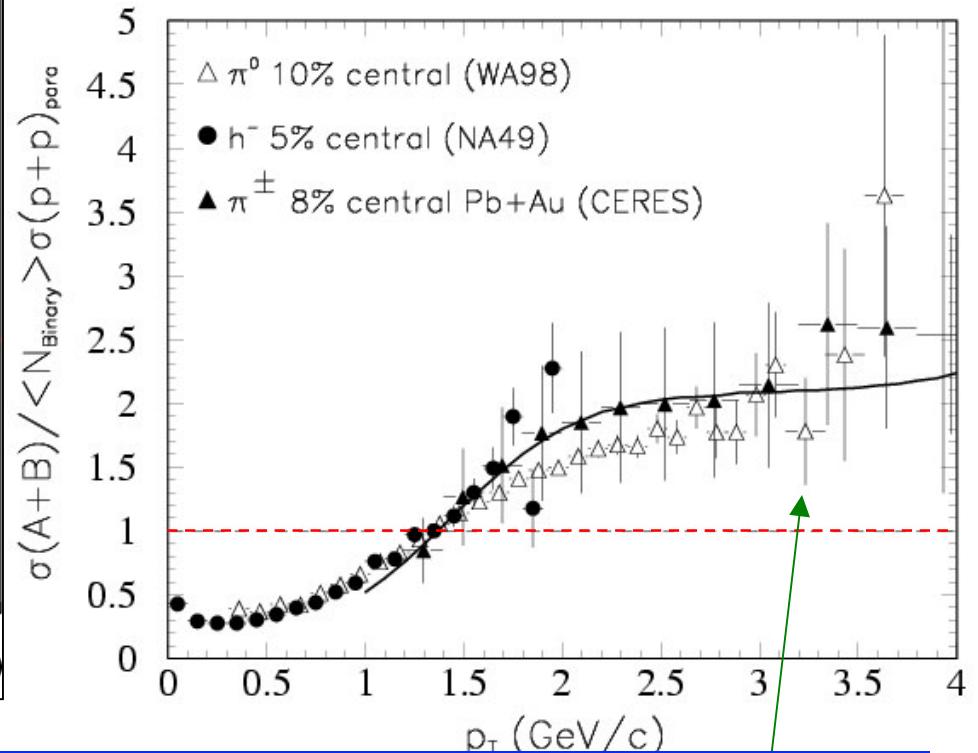
See talk by Hui Long , Thursday session 1

13 March, SQM2005

# Nuclear Modification Factor at Low Energy



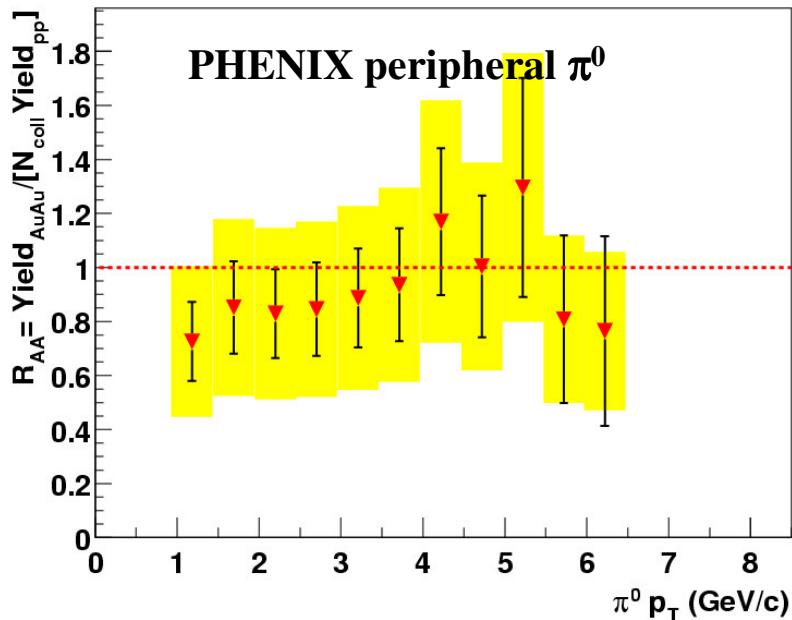
Central Pb+Pb collisions at SPS



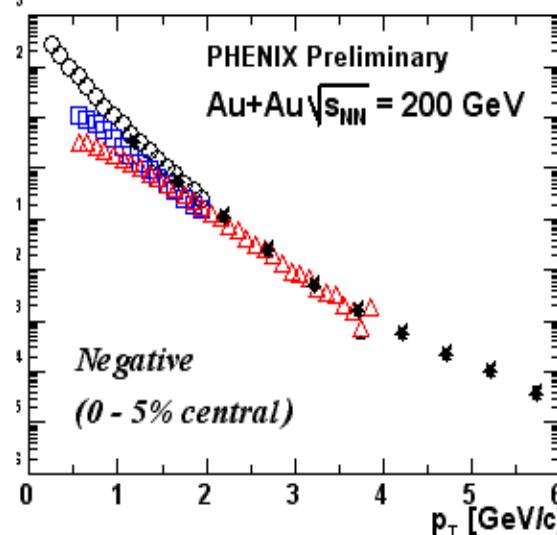
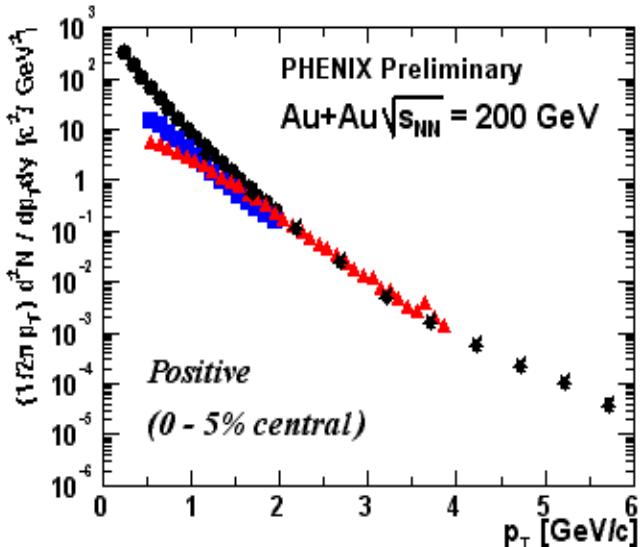
Similar to momentum resolution effect

Steeper spectra(SPS) get affected more -> 2.5 enhancement  
RHIC : theory predicts ~ 1.5

# Can Cronin effect explain the difference between high $p_T$ mesons and baryons ?



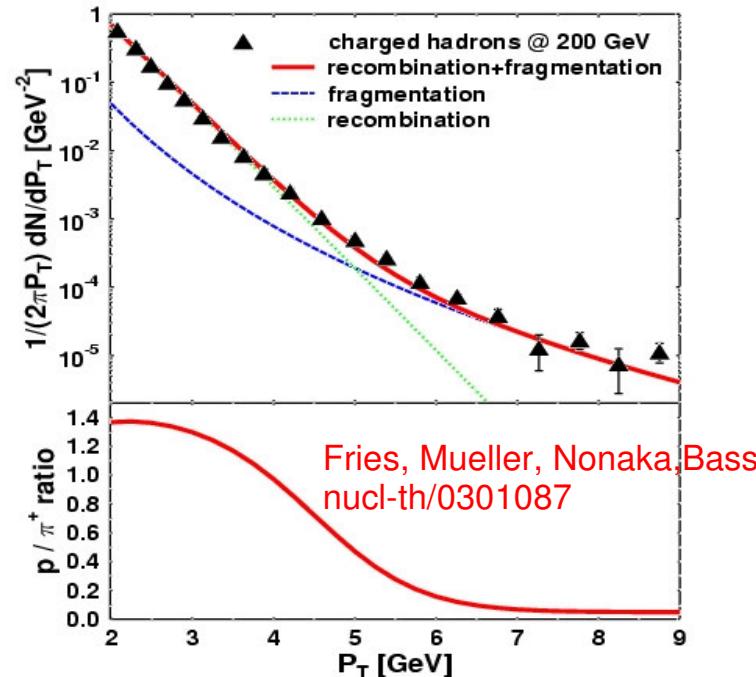
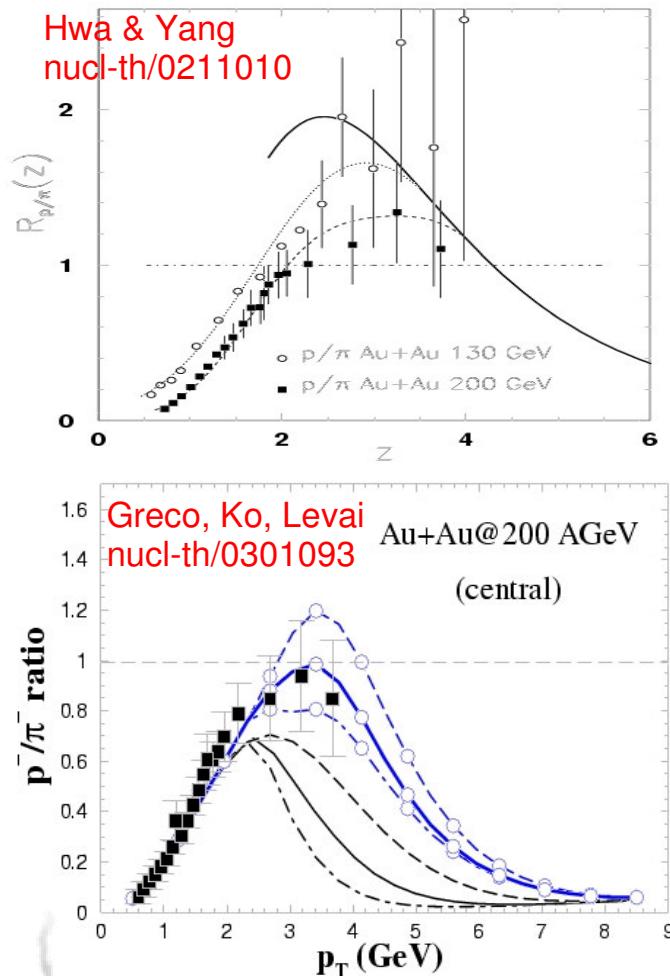
- No Cronin enhancement observed in peripheral  $\pi^0$  data
- Slopes of  $p$ , and  $\pi^0$  the same above 2 GeV/c
- Not likely to have a significantly different behavior for  $p$ ,  $\bar{p}$  and  $\pi^0$



- BUT – wait for the d+Au data. We will have the answer soon!

# Parton recombination and high $p_T$ “chemistry”

The “buzz” word in the last few months: quark recombination/coalescence



- Recombination solves proton puzzle:  
 $p_T(\text{baryons}) > p_T(\text{mesons}) > p_T(\text{quarks})$   
(coalescence from thermal quark distribution ...)
- Pushes soft physics for baryons out to 4-5 GeV/c
- Some exotic explanations (e.g. gluon junctions)



, SQM2003

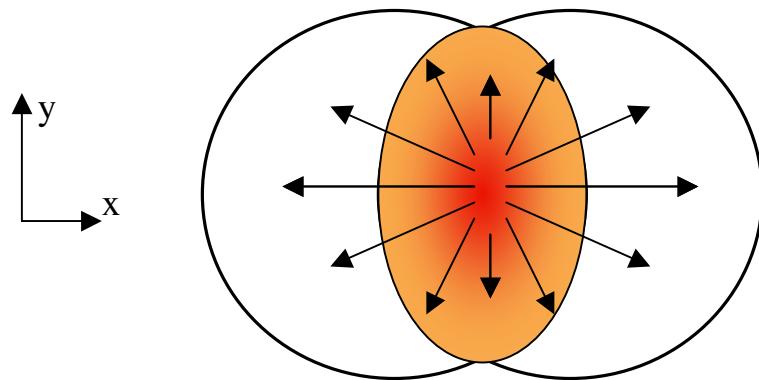
Do we have another smoking gun?

See talk by R. Fries,  
Thursday, session 2

# Azimuthal Anisotropy of Particle Emission

low  $p_T$

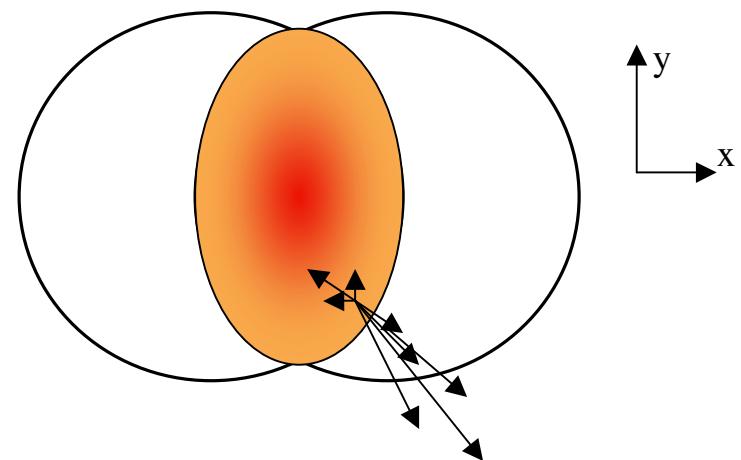
Bulk (Hydrodynamic) Matter



Pressure gradient  
converts position space  
anisotropy to  
momentum space  
anisotropy.

high  $p_T$

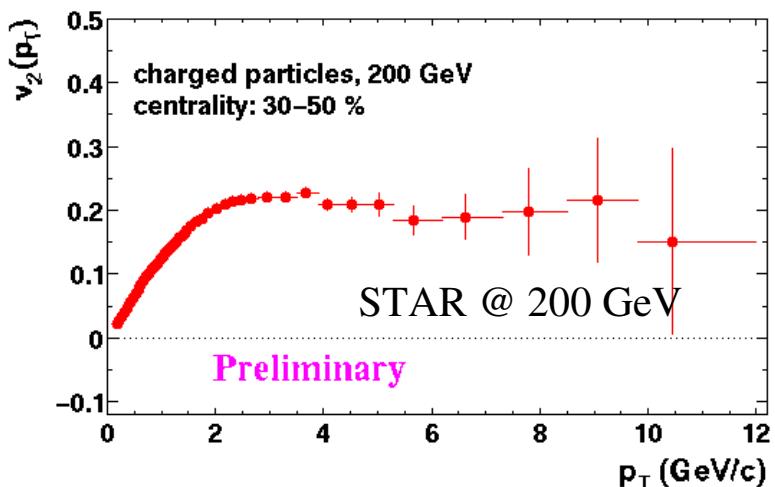
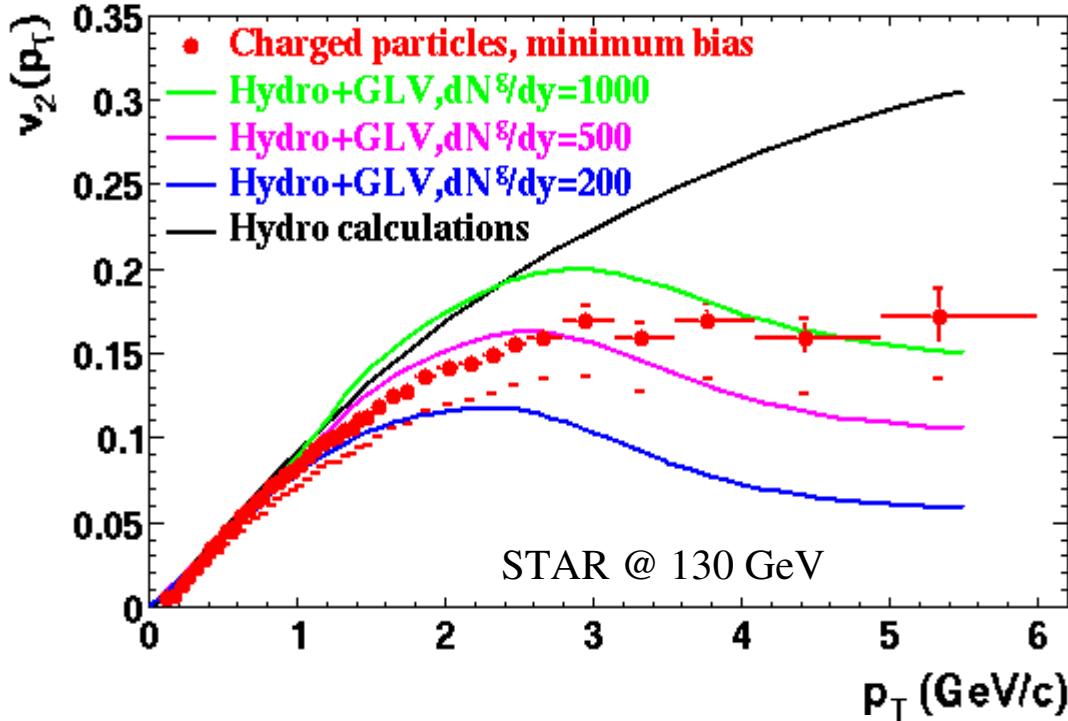
Jet Propagation



Energy loss results  
anisotropy based on  
location of hard  
scattering in collision  
volume.

# Elliptic ‘Flow’ at High- $p_T$

Snellings; Gyulassy, Vitev and Wang (nucl-th/00012092)

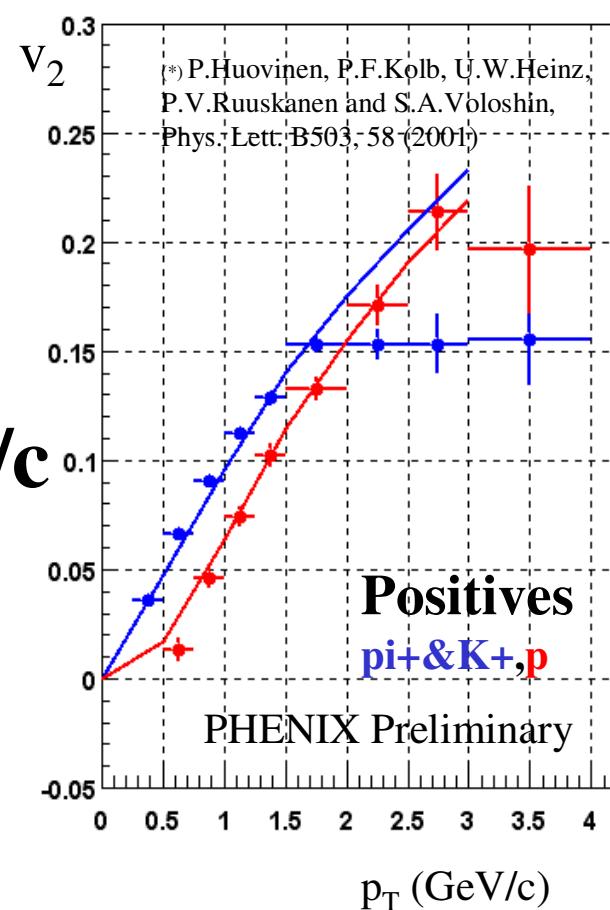
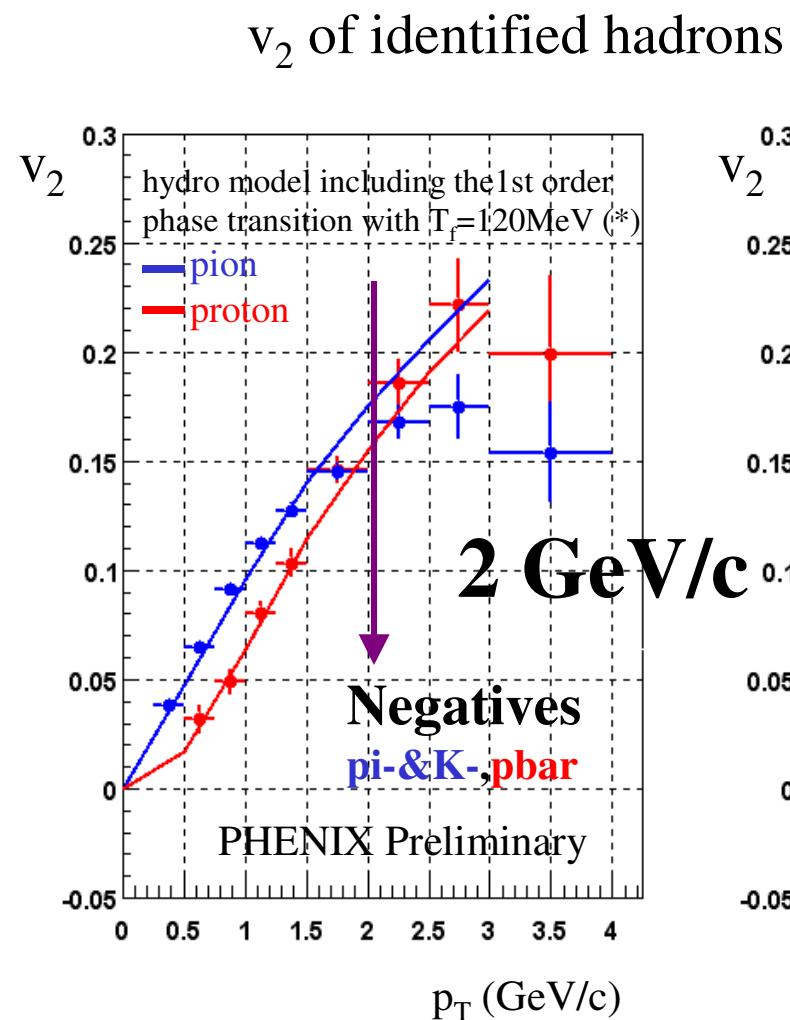


## Hydro + hard scattering model

- hydro up to  $\sim 1.5 \text{ GeV}/c$
- $v_2$  increases with  $p_t$  and saturates  $\sim 2.5 \text{ GeV}$  and decreases towards higher  $p_t$
- saturation value depends on gluon density

**But: data constant to  $\sim 12 \text{ GeV}$**

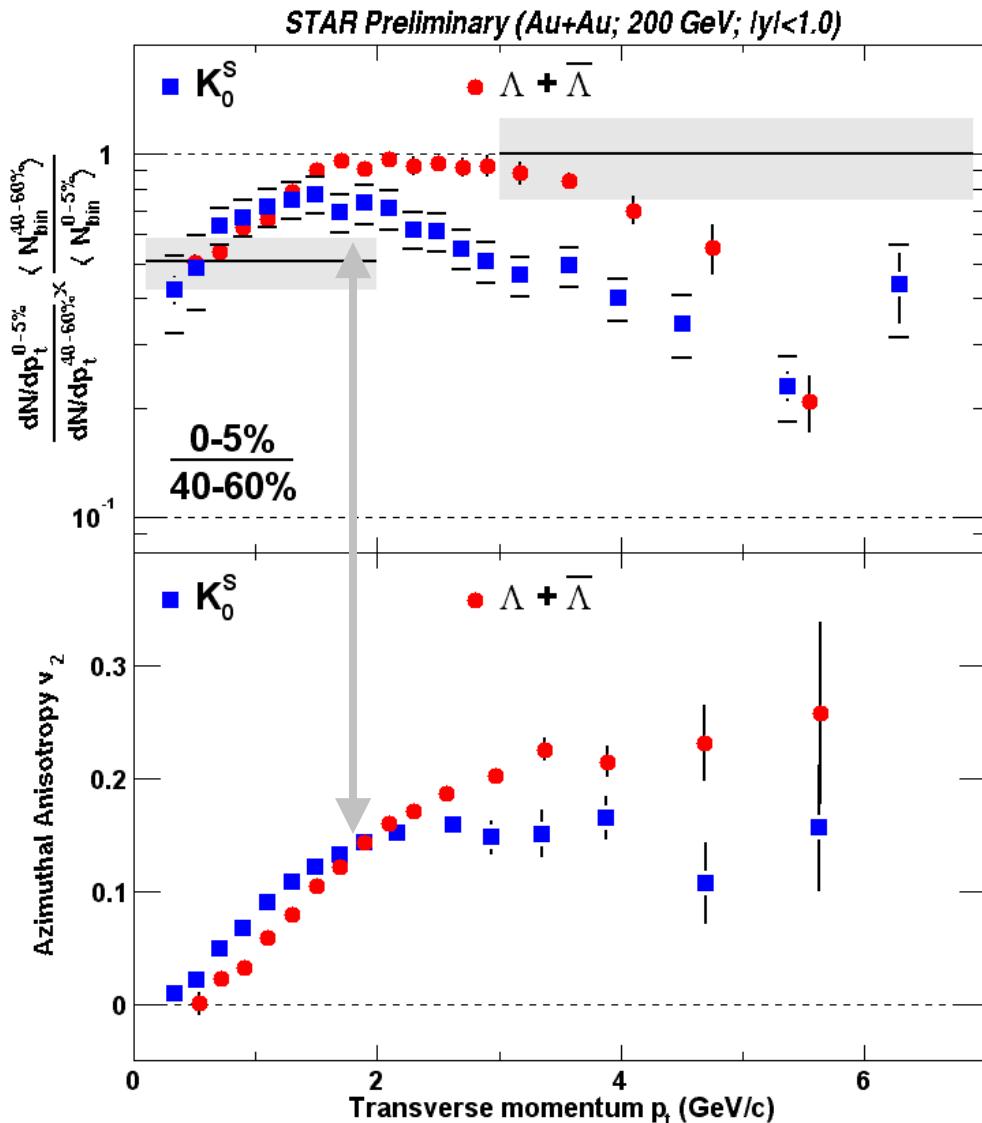
# Elliptic flow of identified particles



Proton v2 exceeds meson v2 above 2 GeV

BNL)

# Species dependence of $v_2$ and $R_{AA}$ vs. $p_T$ from STAR



- At  $p_T \sim 2$  GeV – the baryon  $v_2$  exceeds the meson  $v_2$  for strange particles, too
- Saturation in  $v_2$  and suppression in  $R_{AA}$  seem to be related
- Parton coalescence has also been put forward to explain the  $v_2$  data. See talk by D.Molnar, Thursday, session 2
- Baryon junctions+ quenched component also proposed

See talk by P. Sorensen, Thursday, session 2

## The “strange” high- $p_T$ results from RHIC

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- Species dependent suppression of hadrons with high- $p_T$
- Baryons are not suppressed in the region 2-4 GeV/c.  
Suppression sets in at  $p_T \sim 4$  GeV and merges with the meson suppression around 5-6 GeV/c
- Away side jets disappear in central events
- Large  $v_2$  up to high  $p_T$ .
- Species dependent  $v_2$  saturation level and saturation  $p_T$
- Baryon elliptic flow stronger than that of mesons at high  $p_T$  ( contrary to hydrodynamic behavior)
- Seemingly – there is a correspondence between the  $p_T$  at which  $v_2$  saturates and the onset of suppression.

# Outlook

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- d Au will give some answers , but not all
  - Is hadron suppression is due to jet quenching or CGC ?
  - Measure Cronin effect at RHIC energy
    - see how baryons and mesons are affected
    - have a better handle to disentangle quenching in AuAu
  - Unfortunately, can not distinguish between radial flow and quark coalescence, since both should disappear in dAu
    - Need to measure as many as possible identified particles to high  $p_T$  in AuAu – study mass vs baryon effects
    - *Need more detailed predictions from the theorists*
  - Baryon junctions, if they exist, should be still there in dAu, but overwhelmed by unquenched pions
    - *Is there a more direct signature for baryon junctions ?*
- Stay tuned for new “strange” high- $p_T$  results from RHIC